Power System Harmonics - Analysis, Effects and Mitigation Solutions for Power Quality Improvement

Ahmed F. Zobaa[1,] Shady H.E. Abdel Aleem[2], and Murat E. Balci[3]

[1]College of Engineering, Design & Physical Sciences, Brunel University London, Uxbridge, UB8 3PH, United Kingdom. azobaa@ieee.org

[2]15th of May Higher Institute of Engineering, Mathematical and Physical Sciences, Cairo, Egypt. engyshady@ieee.org

[3]Electrical and Electronics Engineering, Balikesir University, Balikesir, Turkey. mbalci@balikesir.edu.tr

1.1 Introduction

Nowadays, electrical utilities and consumers are paying much attention to enhance the quality of the generated and distributed electrical energy. The main aims are to produce clean electrical power and to distribute it to the end-customers with acceptable power quality performance in a cost-effective manner. Nowadays, the importance of power quality aspects has increased due to the booming developments in power-electronic devices and renewable energy resources under the umbrella of smart grids. Besides, the deregulation of the electricity market resulted in a competitive market in which multiple utility companies try to deliver the best products (generated electrical energy) for the customers who have the chance to choose the utility company that provides them with electrical energy with the highest quality level. In consequence, power quality will play essential role in modern electrical power systems. However, there are also difficulties before wider applicability is possible for the power quality performance limits. One difficulty is that, to date, there is no single commonly approved definition of power quality because of the various power quality perspectives and phenomena [1]. As well, power quality has dissimilar interpretations for people in various electric entities. Some express power quality as the voltage quality, others express it as the current quality and some practice power quality as the system reliability. Furthermore, IEEE Std. 1100 [2] defines power quality as “the concept of powering and grounding sensitive electronic equipment in a manner suitable for the equipment”. One can say that everyone describes it from his own perspective.

On one side, voltage quality focuses on variations of voltage from its ideal waveform (that is characterized by a sine wave of constant magnitude and frequency), while current quality is concerned with the deviation of the current from the ideal sinusoidal waveform. On the other side, discrimination of power quality as a voltage quality or current quality is an ambiguous way of thinking as a deviation in voltage can result in a deviation in current and vice versa. Thus, in order to keep generality, and as the power is mathematically the voltage times current; power quality should be the combination of both voltage and current qualities [3] and is signified by a set of electrical limitations (reference boundaries/margins) that enables an equipment to operate in its planned manner without major operating losses [4], [5] to long-live as possible.

1.2 Disturbances

All electrical equipment may fail or malfunction when come across power quality disturbances, depending on the severity of the disturbance. It is essential for engineers, technicians, manufacturers, and power system operators to well understand and face the several power quality disturbances.

Power quality issues include voltage variations (dips, interruptions, flicker, etc.), transients (surges, lightning, switching events), and grounding issues. Fig. 1.1 summarizes the common power quality problems.

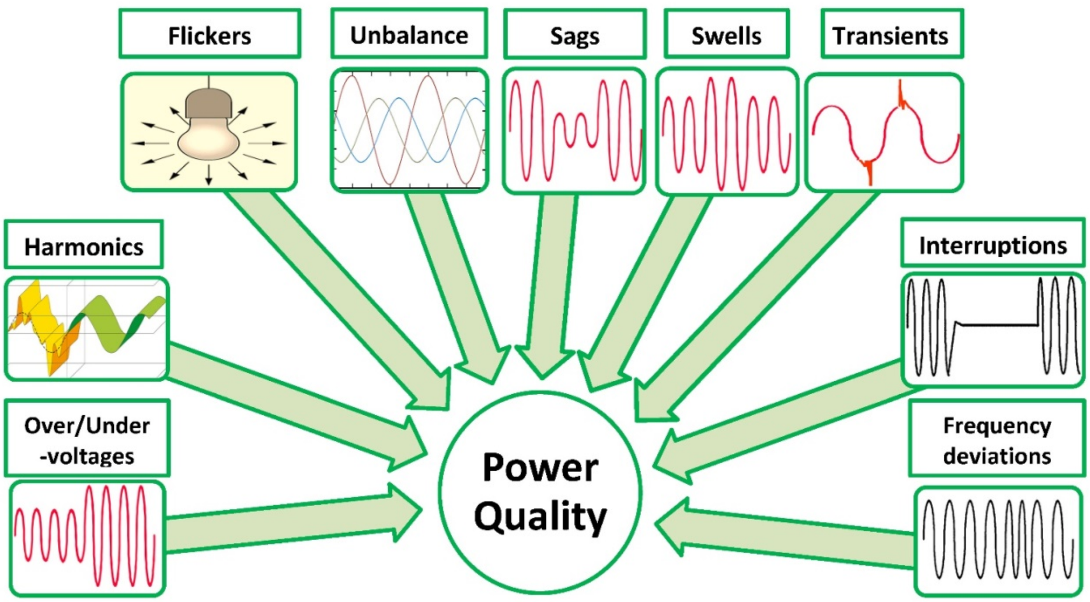

Fig. 1.1 The common power quality problems.

To generalize, power quality issues cover many power system problems like impulsive and oscillatory transients, different types of interruptions, voltage sags and swells, imbalance, under- and over-voltages, notching, noise, harmonics and inter-harmonics, voltage fluctuations and flickers, and power frequency variations [6]. In the following sections, these power quality problems are presented.

1.2.1 Over-voltages and under-voltages

Over-voltage are defined as any voltage greater than that the equipment nominal operating voltage which the equipment is specified to operate at for a time period that exceeds 1 min. While the under voltage can be defined as any voltage below the nominal operating voltage of the equipment for a time period that exceeds 1 min.

Over-voltage phenomenon has many causes in power system networks such as sudden changes in the system operating settings, abrupt load rejection, series/parallel harmonic resonance cases, sudden line-to-ground faults, improper earthing schemes, poor voltage regulation throughout the system, and over-compensation of the reactive power support provided by capacitor banks. Under-voltages can result from improper power cables sizing, long feeder routes with high loading capacities, and large motor starting conditions.

Over-voltage has serious impacts on electrical equipment and power systems as it stresses the equipment's insulation and may damage it, in addition to protective devices tripping because of dielectric failure. Also, overvoltage may lead to flash-over between line and ground at the weakest point in the system and can cause breakdown of the equipment insulation. On the other hand, under-voltage causes an increase of the system losses and results in voltage stability problems. Also, different operational problems may arise due to under voltages such as motors starting problems and protection relays tripping [7].

1.2.2 Voltage flickers

Voltage flickers are defined as a continuous rapid variation of input supply voltage sustained for an appropriate period to enable visual recognition of a variation in electric light intensity. Flicker is a low-frequency p problem in which the magnitude of the voltage or frequency changes at such a rate as to be noticeable to the human eye [6]. The main causes of the voltage flicker are the loads that draw large starting currents during initial energization such as elevators, arc furnaces, and arc welders. If load starting cases are rapidly repeated, then light flicker effects can be quite noticeable. The severity of voltage flickers is measured using short-term and long-term flicker severity terms, where an expected flicker severity over a short-duration (typically 10 minutes) is known as P_{st}, and that evaluated over a long-duration (typically two hours) is known as P_{lt}. Thus, P_{lt} is a combination of twelve P_{st} values.

$$P_{st} = \sqrt{\left(0.0314\times P_a\right)+\left(0.0525\times P_b\right)+\left(0.0657\times P_c\right)+\left(0.28\times P_d\right)+\left(0.08\times P_e\right)} \quad (1)$$

where P_a, P_b, P_c, P_d, and P_e are the surpassed flicker levels during 0.1, 1, 3, 10 and 50% of the surveillance period. By definition, a value of one for P_{st} expresses a visible disturbance, a level of optical severity at which fifty percentage of persons might sense a flicker in a 60-W incandescent lamp. Excessive light flicker can cause a severe headache and can lead to the so-called 'sick building syndrome'.

1.2.3 Voltage unbalance

Voltage unbalance problem is an important power quality issue that can be defined as "a condition in a three-phase system in which the root-mean-square (rms) magnitudes and/or phase angles of the fundamental components of the phase voltages are not all equal" [7]. The principal reason of voltage unbalance in a system is the unbalanced loads among the three phases of the network. This asymmetric loading cause unequal phase currents to flow through the electrical network, causes unsymmetrical voltages drop on a system feeders [8]. Voltage unbalances result in additional power losses in the system and causes more losses in electric motors, so that it cannot be completely loaded up to its nominal power. In addition, excessive voltage unbalances can lead to protection system tripping and causing electrical supply interruption.

The IEEE 112 [9] defines the voltage unbalance, using a factor called the phase voltage unbalance rate (PVUR), is given in (2), where V_{dev} expresses phase voltage variation from the average line voltage (V_{average}) [10].

$$PVUR = \frac{(V_{dev})Max}{V_{avgerage}} \times 100 \tag{2}$$

1.2.4 Voltage sags

Voltage sags or (American English says sag while British English says dip) According to the IEEE-1159 [11], voltage sag is defined as “a reduction in the rms voltage from 0.1 to 0.9 per unit (pu) for a period of 0.5 cycles to 1 minute”. Voltage sag can be categorized into three types, according to its time duration, to instantaneous, momentary, and temporary sag [12].

Voltage sag results from sudden system faults and switching events of large loads having excessive starting currents such as large motors. Voltage sags impact sensitive electrical devices such as personal computers and communication equipment, as well as excessive sag events may cause loss of data and nuisance operation of protection devices. In addition, programmed industrial processes such as paper-making industries, chip-making machinery, etc. can suffer from power supply shutdown in case of severe voltage sags.

Voltage sags can be calculated using various formulas. For example, Detroit Edison’s sag-score (SS) method defines the “sag score” from the amplitudes of the three-phase voltages. A larger *SS* indicates the more the severity of the event [13].

$$SS = 1 - \left(\frac{V_A + V_B + V_C}{3} \right) \tag{3}$$

1.2.5 Voltage swells

Voltage swell can be defined as a rise in the root-mean-square (rms) voltage for periods that range from 0.5 cycles to 1 minute. Swells are usually produced by electric faults (single line-to-ground), upstream supply failures, heavy load rejection events, and switching off shunt capacitor banks. Voltage swell is categorized according to time duration into three types; instantaneous, momentary, and temporary swells. In addition, voltage sags and swells produced when loads are shifted from one supply source to another such as the transfer from the utility source to the standby emergency generator during a loss of the normal utility power source [14].

Voltage swell has harmful effects on electrical power system operation as it leads to aging of electrical connections, flickering of lights, semiconductor damage in power-electronic devices, and insulation deterioration of the equipment.

1.2.6 Transients

In general, most power quality problems are thought as transient events if they exist for a short-duration. Impulsive and oscillatory are the main categories of transients. They are briefed as follows:

A- Impulsive transients

Impulsive transients are abrupt high magnitude actions that cause voltage and/or current levels rise in either a positive or a negative direction for a very short period fewer than 50 ns.

B- Oscillatory transients

An oscillatory transient is an abrupt variation in the steady-state voltage, current, or both, fluctuating at the natural frequency of the system at both the positive and negative directions.

Events causing transients occur from different reasons such as lightning strikes, poor grounding system, electrostatic discharge, inductive load switching, and fault clearance. Transients may lead to probable data loss in computers, malfunction of electronics equipment and microprocessor-based protection relays.

1.2.7 Interruptions

Interruption is a randomly event that occurs with zero-magnitude voltage or current for a particular time period, where the magnitude of voltage or current are less than 0.1 pu. It is classified in terms of duration and standards as follows:

A- Classification according to prior planning

According to EN 50160 [15], the electrical interruptions can be categorized into two types namely, pre-organized interruptions at which the customers are informed (planned interruptions), and accidental interruptions at which sudden failure of equipment or transient fault take place and it may take a long time to restore the electrical supply. This may be long-interruption or short-interruption based on the fault.

B- Classification according to interruption duration

According to IEEE 1250 [16], the electrical interruptions can be categorized into four types according to the duration of the interruption as presented in Table 1.

Table 1
Electrical interruptions categorized based on their durations

Type of interruption	Duration starts at	Duration ends at
Instantaneous	0.5 cycles	30 cycles
Momentary	30 cycles	2 seconds
Temporary	2 seconds	2 minutes
Sustained	Longer than 2 minutes	

Momentary interruptions may cause a complete loss of voltage while sustained interruptions are generally noticed in case of permanent short circuit faults.

1.2.8 Frequency deviation

The fundamental frequency varies from its rated (50 or 60 Hz) value. This frequency deviation is infrequent in stable and stiff interconnected power system networks. However, it can be noticed in weak power systems fed from local generators especially, during sudden load application or rejection conditions. The operating frequency range should be kept within ± 1%

the rated frequency during 95% of the week, and -6%/+4% during 100% of the week [1], [16]. The ratio of frequency deviation (RFD) can be defined as follows:

$$RFD = \frac{|f_m - f_r|}{f_r} \times 100 \tag{4}$$

where f_m is the measured frequency which is time-varying quantity and f_r is the rated system frequency.

1.2.9 Power system harmonics

Most of today's power system waves are distorted. By definition, "any periodically distorted waveform can be represented as a sum of pure sine waves in which the frequency of each sinusoid is an integer multiple of the fundamental frequency of the distorted wave. This multiple is called the harmonic of the fundamental". The sum of sinusoids is referred to as a "Fourier series".

In the last years, all have focused attention on power system harmonics as the most severe issue in the power quality frequent disturbances, because it has adverse impacts on both the utility and consumers, alike. Sometimes, when the terminology of power quality arises, some people routinely predict that the issue is related to power system harmonic distortion. In the past, the terms of power quality and power system harmonics have been incorrectly interchanged.

1.2.9.1 Harmonics sources

At present, as a consequence of the extensive use of power electronic-based components in all power system applications, most of today's loads are nonlinear. To generalize, three categories can be recognized as primary sources of harmonics in power systems [6]. They are given as follows:

- Magnetic core-based equipment as electric motors, power transformers, and generators.
- Arc and induction, and arc welders.
- Power electronic-based equipment.

On one hand, if the power system is characterized by series and shunt elements; thus, the nonlinearities exist in the system are mainly introduced by the shunt elements, such as loads. On the other hand, a series impedance of the power delivery system (impedance between the source and the load) is particularly linear, i.e. short-circuit or Thevenin impedance of a system. Even within a power transformer, the shunt branch (magnetizing impedance) of the standard T model is the source of harmonics, whilst the series leakage impedance is considered a linear element.

Today, the most prevailing harmonic sources are:

- Converters (rectifiers and inverters).
- Switch-mode power supplies.
- The different forms of pulse modulation which are employed in active power and voltage control in transmission circuits.
- High-frequency converters needed for induction heating.
- Thyristor controlled reactors.

- Rectifiers and inverters of grid-connected solar photovoltaic cells and windmills.
- Magnetizing currents of the transformers.
- Excitation currents of the rotating machines.
- Flexible AC transmission systems (FACTS).
- Uninterruptible power supplies.
- Rectifiers and inverters of HVDC systems.
- Static power converters using thyristor to control speed and torque of variable speed drives.
- Controlled arc welders, controlled furnaces and ovens.
- Induction motors working in the saturation region.
- Electrolysis loads (aluminum smelters and battery-charging plants.
- Ballasts in high-power fluorescent discharge lamps.

1.2.9.2 Harmonics effects

Impact of harmonics can range from degradation of performance of equipment to its serious failure. The effects of power system harmonics can be clustered into two broad groups, as effects on power system networks and equipment, and effects on telecommunication systems.
The most common consequences on the different sectors of an electrical system are summarized below [17].

- Excessive energy losses due to the high non-sinusoidal currents; thus, high electricity bills.
- The presence of current in the neutral wire with additional losses. An overheating problem may occur.
- Equipment failure, standstill of motors, overloading of conductors, blowing of fuses and blackouts of lamps.
- Errors in metering of energy consumption.
- Interference with telecommunication systems and networks.
- Data loss in data-transmission systems.
- Malfunction of control and protection system performance.
- Series and parallel harmonic resonance, which may cause system component damage, equipment failure, and service interruption.
- Harmonic instability which leads to damage of generator shafts.
- Audible noise in transformers and rotating machines and motor vibrations.
- Computer and programmable logic controllers' lockups and in correct operation.
- Malfunctioning of voltage and generator regulators with frequent maintenance issues.
- Premature aging of equipment.
- UPS sizing issues.
- Worsening of loads' power factor with its adverse consequences and utility's imposed penalties.

1.3 Solutions

A thorough understanding of electrical system related problems is helpful to implement good power conditioners and custom power devices to enhance power quality. Today, it is assumed that most of our electrical loads become nonlinear in nature. Generally, power factor improvement and other power quality-based equipment are the two main groups of solutions that can enhance power quality performance in a system, thus:

A- Power factor improvement equipment [17]-[24]

- Power factor correction capacitors.
- Harmonic filters; especially passive filters.

These solutions certainly guarantee energy bill savings from reduction of low power factor penalties, not power or energy savings [24].

B- Other power quality-based equipment [17], [24]-[27]

- Inline reactors or chokes.
- Harmonic mitigating and K- factor transformers.
- Neutral blocking filter.
- Negative sequence current reduction.
- Passive, active and hybrid filters.
- Surge protection.
- Soft starters.
- Zigzag reactors.
- Conservation voltage reduction.
- Green plug filters, FACTS, and D-FACTS.
- Multiple pulse converters.

These solutions can enhance power quality but with no real savings [24].

Each power quality solution has its own merits and drawbacks at different circumstances. Consequently, selection of a precise solution to solve a power quality problem necessitates familiarity with the different technologies to ensure that it is the proper techno-economic solution for an application.

Besides, as the grids transition towards low-carbon technologies, the use of power electronics becomes wide-spread. Also, renewable sources may introduce harmonic distortions which may adversely affect consumer equipment, but also monitoring and control devices that maintain the operational status of the grids themselves, which can lead to large-scale blackouts and significant losses in power networks. Therefore, it is imperative that novel solutions be sought to enable networks to cope with future developments.

Finally, power quality issues cover many power system problems such as under- and over-voltages, voltage sags and swells, transients (impulsive and oscillatory), interruptions, voltage unbalance, harmonics and inter-harmonics, voltage fluctuations and flickers, and power frequency variations. In this introductory chapter, a quick brief on power quality concepts and issues are presented.

References

1. G. S. Elbasuony, S. H. E. Abdel Aleem, A. M. Ibrahim, and A. M. Sharaf, "A unified index for power quality evaluation in distributed generation systems," Energy, vol. 149, pp. 607–622, Apr. 2018.
2. IEEE Std. 1159-2009, IEEE Recommended Practice for Monitoring Electric Power Quality. 2009. doi:10.1109/IEEESTD.2009.5154067.
3. M. Bollen and I. Gu, Signal processing of power quality disturbances. 2006.
4. J. B. Dixit, A. Yadav, "Electrical Power Quality. Laxmi Publications", Ltd., 2010.
5. S. H. E. A. Aleem, M. E. Balci, A. F. Zobaa and S. Sakar, "Optimal passive filter design for effective utilization of cables and transformers under non-sinusoidal conditions," 2014 16th International Conference on Harmonics and Quality of Power (ICHQP), Bucharest, 2014, pp. 626-630.
6. R. C. Dugan, M. F. M. Granaghan, S. Santoso, and H. W. Beaty, "Electric Power Systems Quality", 2nd ed., New York: McGraw-Hill, 2002.
7. M. S. Kurt, M. E. Balci, and S. H. E. Abdel Aleem, "Algorithm for estimating derating of induction motors supplied with under/over unbalanced voltages using response surface methodology," *J. Eng.*, vol. 2017, no. 12, p. 627–633(6), Dec. 2017.
8. A. Baggini, Handbook of power quality. John Wiley & Sons. 2008
9. IEEE Standard 112-1991. IEEE standard test procedure for polyphase induction motors and generators; 1991.
10. A. M. Saeed *et al.*, "Power conditioning using dynamic voltage restorers under different voltage sag types," *J. Adv. Res.*, vol. 7, no. 1, pp. 95–103, Jan. 2016.
11. IEEE Std. 1159-2009, IEEE Recommended Practice for Monitoring Electric Power Quality. 2009. doi:10.1109/IEEESTD.2009.5154067.
12. A. F. Zobaa, and S.H.E. Abdel Aleem (ed.), Power Quality in Future Electrical Power Systems, Energy Engineering, IET Digital Library, 2017.
13. Polycarpou A. Power Quality and Voltage Sag Indices in Electrical Power Systems-Electrical Generation and Distribution Systems and Power Quality Disturbances. In: Romero G, Editor., InTech; 2011, p. 140–60. doi: 10.5772/18181 **.**
14. C. Sankaran, Power Quality. CRC press. 2001.
15. EN 50160, Voltage characteristics of electricity supplied by public distribution systems, 1999**.**
16. IEEE Std 1250-2011, IEEE Guide for Identifying and Improving Voltage Quality in Power Systems**.**
17. D. J. Carnovale, "Applying Harmonic Solutions to Commercial and Industrial Power Systems," Eaton, Cutler-Hammer, Moon Township, PA, Boston, 2003**.**
18. M. M. A. Aziz, E.-D. El-Zahab, A. M. Ibrahim, and A. F. Zobaa, "Practical considerations regarding power factor for nonlinear loads," IEEE Trans. power Deliv., vol. 19, no. 1, pp. 337–341, 2004.

19. M. E. Balci, S. H. E. Abdel Aleem, A. F. Zobaa, and S. Sakar, “An algorithm for optimal sizing of the capacitor banks under nonsinusoidal and unbalanced conditions,” *Recent Adv. Electr. Electron. Eng.*, vol. 7, no. 2, 2014.
20. S. H. E. A. Aleem, A. F. Zobaa, and M. E. Balci, “Optimal resonance-free third-order high-pass filters based on minimization of the total cost of the filters using Crow Search Algorithm,” *Electr. Power Syst. Res.*, vol. 151, no. C, pp. 381–394, 2017.
21. Independent pricing and regulatory tribunal of new south wales, method guide power factor correction energy savings formula: deemed energy savings method. Energy savings scheme, Jan. 2015. [Online]. Available: http://www.ess.nsw.gov.au/files/353708d1-ab17-4aa4-96a5-a41b0103d03f/Method_Guide_-_Power_Factor_Correction_-_V20.pdf
22. S. H. E. A. Aleem, M. T. Elmathana, and A. F. Zobaa, “Different design approaches of shunt passive harmonic filters based on IEEE Std. 519-1992 and IEEE Std. 18-2002,” *Recent Patents Electr. Electron. Eng.*, vol. 6, no. 1, pp. 68–75, 2013.
23. Islam F. Mohamed, Shady H. E. Abdel Aleem, Ahmed M. Ibrahim & Ahmed F. Zobaa (2014) Optimal Sizing of C-Type Passive Filters under Non-Sinusoidal Conditions, Energy Technology & Policy, 1:1, 35-44, DOI: 10.1080/23317000.2014.969453
24. D. J. Carnovale and T. J. Hronek, “Power quality solutions and energy savings—what is real?,” *Energy Eng. J. Assoc. Energy Eng.*, vol. 106, no. 3, pp. 26–50, 2009.
25. K. Z. Heetun, S. H. E. Abdel Aleem, A. F. Zobaa, S. H. E. A. Aleem, and A. F. Zobaa, “Voltage stability analysis of grid-connected wind farms with FACTS: Static and dynamic analysis,” *Energy Policy Res.*, vol. 3, no. 1, pp. 1–12, Jan. 2016.
26. F. H. Gandoman, A. M. Sharaf, et al., “Distributed FACTS stabilization scheme for efficient utilization of distributed wind energy systems,” *Int Trans Electr Energ Syst.*, vol. 27, no. 11, p. e2391, 2017.
27. Smart ways to cut down the influence of harmonics. [Online]. Available: http://electrical-engineering-portal.com/smart-ways-to-cut-down-the-influence-of-harmonics